

Selective Enhancement of RDF Fuels

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SELECTIVE ENHANCEMENT OF RDF FUELS

by

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in the problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report presents information resulting from a study of chemical and thermal treatments to improve the quality of the products derived from the organic fraction of municipal solid waste. Powdered fuels prepared from RDF were evaluated in coal and oil burning combustion units. The performance of these fuels is described in depth. It is hoped that the information provided in this report will be of assistance to researchers and developers concerned with resource recovery endeavors.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

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ABSTRACT

Conversion of the organic fraction of municipal solid waste to a powdered fuel offers a number of advantages for improving both the quality and marketability of the product. Cellulose embrittlement processes have been developed to convert the organic fraction of MSW to a powder. This project concentrated on improving the embrittlement process developed in an earlier study and characterizing the properties of the powdered fuel obtained. Over 363 kg. (800 lb.) of powdered fuel were processed for characterization studies. The processing procedures used for converting the RDF from the Americology plant in Milwaukee is described in detail. In the initial phase of this project, the physical, chemical and thermal properties of the powdered fuel were evaluated. Particle size distribution, morphology and density were measured. Proximate, ultimate and ash analysis were determined and TGA, DTA and heat content were established. In the second phase of this project, the combustion characteristics of the powder alone and mixed with powdered coal and oil were extensively evaluated. This report was submitted in fulfillment of Grant No. R-806535010 by the University of Dayton Research Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers work performed during the period August 1, 1979 to July 31, 1980.

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CONTENTS

Foreword	iii
Abstract	iv
Figures.	vi
Tables	vii
Conversions	viii
Acknowledgement	ix

1. Introduction.	1
2. Conclusions and Recommendations	2
3. Background - Cellulose Embrittlement.	6
4. Powder Preparation	11
5. Powder Characterization	15
6. Powder/Oil Slurries	29
7. Investigation of the Burning Characteristics of the Powdered RDF Coal and Powder/Oil.	34
References.	43

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FIGURES

<u>Number</u>		<u>Page</u>
1	Chemical structure of cellulose	7
2	Properties of cellulose materials	7
3	Possible embrittlement mechanism	10
4	Process flow diagram	12
5	Pilot reactor	13
6	149 μ (100 mesh) material at 100X	16
7	74 μ (200 mesh) material at 100X	16
8	149 μ (100 mesh) material at 300X	17
9	74 μ (200 mesh) material at 300X	17
10	149 μ (100 mesh) particles at 300X	18
11	74 μ (200 mesh) particles at 300X	18
12	Thermogram of RDF powder fuel	24
13	Burning profile of RDF powder fuel	25
14	DTA plot	26
15	Combustion setup	35
16	Battelle-Columbus Combustion Research Facility	40

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vi

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TABLES

<u>Number</u>		<u>Page</u>
1	Biomass Material Compositions	6
2	Powder Processing Conditions	11
3	Particle Size Distribution and Moisture Content of Powdered RDF	15
4	Density of Minus 149 μ (-100 Mesh) Powder	19
5	Proximate Analysis	20
6	Ultimate Analysis	20
7	Fusion Temperature of Ash	20
8	Ash Analysis	21
9	Ash Distribution in RDF Powder	21
10	Heat Content of RDF powder	23
11	Thermal Analysis of Powdered RDF	27
12	Preliminary Evaluation of Oil/Powder Slurry	32
13	Density and Viscosity of Oil and Powder/Oil Slurry	33
14	Results of the Combustor Experiments	37
15	Summary of 15% RDF Powder in Distillate Oil Combustion Experiments	42
16	Summary of 30% RDF Powder in Distillate Oil Combustion Experiments	42

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CONVERSIONS

tons x 0.9 = metric tons

yd³ x 0.76 = m³

ft x 0.3 = m

ft² x 0.09 = m²

ft³ x 0.027 = m³

in x 2.54 = cm

lb x 0.45 = kg

million BTU x 1.054 = mkj

gal x 3.8 = l

qt x 0.95 = l

oz x 28.0 = g

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SECTION 1

INTRODUCTION

The primary purpose of this study was to develop effective processes to convert the organic fraction in MSW into a powder. The processes for converting the organic fraction in MSW to a powdered material offer a number of advantages for improving both the quality and marketability of refuse derived products. In the powdered form the refuse is a more effective fuel, can be used as a filler material in plastic and rubber products and can be used as a feedstock in several biomass conversion processes (acid hydrolysis, pyrolysis, etc.).

This study concentrated on improving the embrittlement process developed in an earlier study⁽¹⁾ and better characterizing the properties of the powder obtained from embrittling RDF from the Americology Plant in Milwaukee. Over 363 kg (800 lb.) of RDF were processed and the combustion characteristics of RDF powder, powder/coal and powder/oil mixtures were extensively investigated.

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SECTION 2

CONCLUSION AND RECOMMENDATIONS

SUMMARY OF FINDINGS

During the course of this study, over 363 kg (800 lb) of RDF were processed by embrittlement treatment for conversion to a fine powder. The major objective of this project was the evaluation of the RDF powder as a fuel. The powder produced was characterized and its combustion performance with powdered coal and in an oil slurry were measured.

Powder Characterization

The powder obtained by the embrittlement of RDF consists primarily of short choppy fibers minus 150 μ (-100 mesh) in size. Dispersed in the fibrous mix are irregular shaped inert materials (predominantly silicate glasses). The powder contained 5 to 7 1/2 percent moisture and 25 to 44 percent noncombustible material. The high quantity of noncombustibles (glass, metal and minerals) is a characteristic of the RDF prepared by Americology in Milwaukee and will vary considerably for different processes and for different areas of the country. From the proximate and ultimate analysis it was found that the powder contained about 52% volatiles, had a carbon content of 35%, and a chlorine content of 3%. The powder had a loose density of 271 kg/m³ (16.9 lb/ft³) and an average heat content of 13025 MJ/kg (5600 BTU/lb). If an RDF with lower inert content were used, a higher heat content would be obtained. The inert fraction of the powder was analyzed to be a calcium, magnesium, sodium, aluminum silicate low in iron. It had a fusion temperature above 1360°C (2480°F). Based on TG and DT analysis it is observed that the RDF powder is easily ignited (ignition temperature, 277°C (530°F)) and burns readily.

Compared to powdered coal the RDF powder has a lower ignition temperature, higher volatile content, much lower carbon content, about half the heat content, twice the ash content, one-tenth the sulfur, fifteen times the chlorine content and is four-tenths the density. As a fuel the RDF powder will ignite and burn more rapidly than coal, but it will generate less thermal energy. Combustion products will present about as much corrosion problems as coal (C1 versus S) but should present greater handling problems because of a lower density and a high ash content.

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Powder/Oil Slurries

Suspension of the RDF powder in a fuel oil offers a number of advantages for enhancing the use of the RDF powder as a fuel (easier transport and storage, greater safety, etc). The procedure for preparing powder/oil slurries and selected properties were evaluated.

The powdered RDF can be easily slurried in oil up to about 40 weight percent. The only problem encountered was the sedimentation of the powder within four hours. However, more stable suspensions (in excess of 20 hr) were obtained with small (1%) additions of a dispersion agent (Rheotol). As would be expected the density and viscosity of the powder/oil slurry is considerably higher than the pure fuel oil ($\rho \sim 1\text{g/cm}^3, \mu = 32\text{ cp}$). The stabilized slurry does not appear to present transport and handling difficulties, however, long term experience with these fuel mixtures will be required.

COMBUSTION STUDIES

RDF Powder and RDF Powder/Coal Mixtures

The RDF powder and RDF powder/coal mixtures were fired in a pulverized coal test combustor. The RDF powder and mixtures of 25 and 50 weight percent RDF powder with coal were studied. Although some handling problems were encountered with the RDF powder due to its lower density and heat content, the RDF powder/coal mixtures (particularly the 50/50 blend) handled very well and all the compositions tested burned well. In addition to its good handling characteristics the 50/50 blend proved to be the most effective fuel mix studied. The lower ignition temperature and higher quantity of volatiles in the RDF aided the combustion of the coal.

More complete combustion is also achieved in the coal when it is mixed with the RDF powder. The very low sulfur and alkali content of the RDF powder effectively reduced SO_2 in the combustion gas emissions. However the high chlorine content in the RDF powder may cause corrosion problems and some environmental concerns. The use of a less corrosive embrittling agent (e.g., HNO_3 , H_3PO_4 , O_3 , H_2O_2 , etc), if effective, could reduce or eliminate this problem.

RDF Powder/Oil Slurries

The RDF Powder/Oil slurries with up to 30 weight percent RDF burned well in the test furnace. However, above 15 weight percent there were a number of problems encountered in transporting the slurry. Plugging of the pump and feed lines due to powder sedimentation was the primary problem encountered during the

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combustion tests. The use of a dispersion agent should alleviate this problem. The combustion of the powder/oil slurries produced considerably more ash than is obtained when the oil is burned alone. This causes considerable handling problems since the conventional oil burning units are not designed to process large quantities of ash. The ash content of the RDF powder is likely to be the limiting factor for determining the RDF powder to oil ratio for slurry preparation.

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CONCLUSIONS

An effective procedure for converting RDF to a fine powder by embrittlement treatment has been developed. The RDF powder appears to be an effective fuel compatible with coal and some oil burning equipment. Although the RDF powder can be burned alone or in combination with coal and oil, its best performance was in a mix with pulverized coal. The most promising application for the RDF powder is in a 50/50 mix with pulverized coal. This fuel mixture burns well (better than either component) and results in lower SO_2 emissions.

The major difficulties with the use of the RDF powder as a fuel is the high inert content (ash) and the potential problems from the high chlorine content. The use of screening and other classification processing of the raw refuse should result in a significant reduction of the inert content and the use of different embrittlement reagents (HNO_3 , H_3PO_4 , etc) should eliminate potential corrosion and environmental problems. However, selection of effective unit processing procedures to reduce inert content and selection of a less corrosive embrittlement agent will require additional research studies.

RECOMMENDATIONS

During the course of the work conducted on this project a number of observations have been made pertaining to the effectiveness of the technology, the potential applications of the technology and the areas needing further development. In this work a technology for converting refuse to a fine powder has been established based on the use of cellulose embrittlement techniques. However, the mechanisms of the process are not completely understood and need further elucidation. The identification of effective alternative embrittlement reagents, particularly reagents that would not leave residues which could be corrosive or detrimental in other ways is also needed.

The RDF powder proved to be an effective fuel when used in a 50/50 (by weight percent) mix with pulverized coal. The RDF powder provided considerable enhancement for combustion of the coal. However, more needs to be known about the handling (transport, storage, etc) behavior of both the RDF powder and the

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powder in a 50/50 mix with pulverized coal. In addition, more needs to be known about the emissions from combustion of RDF/coal mixtures.

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It would appear that a variety of biomass materials, particularly cellulose wastes from industrial and agricultural sources (stalks, husks, bark, wood and crop residue, straw, etc) could also be converted to a powder for use as a fuel or as a feedstock for biomass conversions. However, more work is needed to develop effective processing procedures for powdering the variety of biomass materials which might be available for conversion to a powdered fuel.

Based on these observations the following recommendations for future work are proposed: (1) further elucidation of the embrittlement mechanisms; (2) identification of alternate embrittlement reagents; (3) further characterization of the RDF powder mixed with pulverized coal; and (4) extension of the embrittlement process to other biomass materials.

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SECTION 3

BACKGROUND - CELLULOSE EMBRITTLEMENT

In recent years, we have begun to look with renewed interest upon a variety of cellulose waste materials as a promising alternate source of energy. Cellulose and cellulose wastes are categorized as biomass materials and until the mid 1800's these materials (primarily wood) served as a primary fuel source for the United States. Biomass materials can be converted to liquid, solid, or gaseous fuels by a number of chemical, biological, and thermal processes.

Most of the organic waste in municipal and industrial refuse as well as agricultural wastes are termed biomass since they are plant materials or derived from plant materials. Included in this category are waste paper and wood products (newsprint, cardboard, furniture, packaging materials, etc.), crop and food processing residues (straw, corn cobs, husks, etc.), logging and wood manufacturing residues (branches, stumps, bark, sawdust, etc.) as well as manure and sewage sludge.

The major constituents of most biomass materials are cellulose, hemicellulose and lignin. The quantities of each of these constituents vary depending on the type of plant material, the type of processing it received and whether it is a paper or wood product. A tabulation of the general composition for several important types of biomass materials is presented in Table 1.

TABLE 1. BIOMASS MATERIAL COMPOSITIONS

Biomass Material	Composition (%)				
	Cellulose	Hemicellulose	Lignin	Mineral Matter	Waxes, Resins, etc.
Hardwoods	40-55	24-40	18-25	1	2-12
Softwood	45-50	25-35	25-35	1	2-12
Grasses, straw, etc.	25-40	25-50	10-30	2-9	?
Leaves	15-20	85	-	-	tr
Newsprint	40-55	25-40	18-30	1-4	tr
Kraft Paper	60-70	10-20	5-10	2-6	tr

Most biomass materials are cellulosic compounds composed of 15-70 percent cellulose, 10-85 percent hemicellulose and 5-35 percent lignin. Cellulose is a linear glucose polymer of D-anhydro glucopyranose units linked by β -1-4-glucosidic bonds as shown

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in Figure 1. Hemicellulose is a polysaccharide intimately associated with cellulose but with a lower molecular weight. Lignin is a complex polyhydric polymer containing condensed phenolic, open phenolic, condensed ether, open ether and alcoholic groups. These three major constituents are combined into a fibrous structure which makes up the main body of most plant material.

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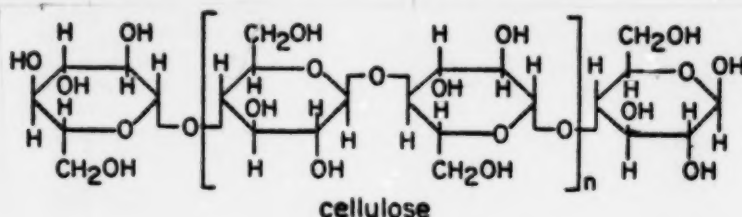


Figure 1. Chemical structure of cellulose.

Wood fiber serves as a good model to demonstrate the complex interrelationship of the cellulose, hemicellulose and lignin constituents. A cross section of a wood fiber as shown in Figure 2 consists of a central cavity (lumen) surrounded by two concentric walls; termed the primary and the secondary wall. The secondary wall which is adjacent to the lumen consists of an inner and outer skin which is mostly cellulose and hemicellulose encasing a middle lamella which is mostly lignin. The primary wall adjacent to the outer skin serves as an elastic membrane around the outside of the fiber and consists mostly of cellulose, hemicellulosic materials, and some lignin. The zone between wood fiber cells is principally lignin. The cellulose fibers in the inner and outer skins are helical around the fiber axis.⁽²⁾

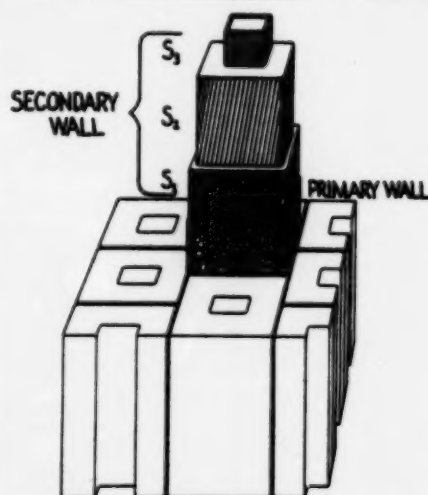


Figure 2. Diagrammatic sketch showing the various layers of wood cell walls. (3)

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The cellulose in the wood fiber has a fibrous morphology consisting of crystalline and amorphous areas. The molecular weight and chain length are variable and in most cases only average values can be determined.

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Wood fibers, because of their pore structure and general cellular nature have a large internal surface area and are highly adsorbent. They have a particularly strong affinity for water. Dry cellulose fibers are some of the most hygroscopic substances known. Most cellulose fibrous materials under normal atmospheric conditions contain 15-30 percent moisture. Water can be in the fibrous structure as bound water, capillary water or imbibed water. Bound water is held by adsorption on the surface of the cellulose crystallites. This water is strongly bonded to the cellulose and no longer exhibits the properties of "free water". Capillary water is found in the fiber pores but is not intimately bound to the cellulose fibers. Imbibed water fills the lumen and coarse pores of the fiber and remains as free water. (2)

Thermal treatments alone can be used to degrade cellulosic materials. Heating above 200°C (392°F) for long periods will result in a loss of fiber structure as well as loss of hygroscopicity. Significant degradation can even be observed at temperatures of 150°C (302°F). Initial studies at the University of Dayton Research Institute (UDRI) showed that thermal treatments resulted in moderate embrittlement of cellulosic materials. (4) This occurs because of the formation of hydrogen or ether bonding between adjacent cellulose molecules.

Treatment of cellulosic materials with oxidizing agents will also cause a breakdown to products of lower molecular weight. These products can vary from practically unchanged fibers to a friable powder. In screening studies performed at the UDRI it was found that exposure of shredded newsprint to Cl_2 (an oxidizing agent), resulted in substantial embrittlement of paper. However, considerable Cl_2 (5.5 percent by weight) was adsorbed by the paper when it was exposed to the embrittlement treatment. It would appear that ozone or H_2O_2 might be a more desirable oxidizing agent since it would not present potential corrosion or pollution problems if it were adsorbed by or reacted with the cellulosic material during treatment.

Mineral acid treatments have been found to be very effective for the embrittlement of cellulosic materials. Nitric, sulfuric, and hydrochloric acid treatments have proved to be the best reagents in the studies conducted at UDRI and in work reported by Combustion Equipment Associates (CEA). (4,5) The work performed

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at CEA served as the basis for the development of a proprietary process for converting MSW to a powder fuel (ECO Fuel - II). The results of the studies at UDRI showed that HCl was the most effective embrittlement agent tried. In addition, it was found that longer treatment times and higher treatment temperatures increased the embrittlement of cellulose waste samples.⁽³⁾

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An understanding of the chemical processes which result in the embrittlement of cellulosic material by HCl treatment is of fundamental importance. Such an understanding would provide a basis for modification and improvement of the present process, and could provide a rationale for subsequent development of alternative processes which avoid the use of expensive and highly corrosive agents such as HCl.

One of the anticipated results from the exposure of moist cellulosic materials to HCl is the hydrolysis of glycoside bonds in the polysaccharide backbone. Viscosity measurements on cupriethylenediamine solutions prepared from HCl-treated paper have in fact confirmed this expectation. Exposure to very low levels of HCl causes a dramatic decrease in the solution viscosity, indicating a decrease in the degree of polymerization (DP). In spite of this decrease in DP, however, these lightly treated cellulosic samples were not significantly embrittled. Based on these observations, it was concluded that embrittlement was not solely the result of a decrease in the DP of cellulose. Our conclusion was reinforced by common experience with over-pulping in the paper industry. Paper produced from pulp having a low DP have certain undesirable characteristics, but friability is not included as one of these. Clearly some other chemical changes must occur subsequent to the hydrolysis process.

A clue to the nature of the embrittlement process was provided by the properties of filter paper which had been heavily treated with HCl. Such samples failed to completely dissolve in the cupriethylenediamine reagent. Like the extent of embrittlement, the lack of solubility appeared to qualitatively correlate with the level of HCl treatment of the filter paper sample. However, meaningful viscosity measurements could not be conducted with these samples owing to their lack of complete solubility.

A causal relationship between reduced solubility and embrittlement has not been established for these extensively treated filter papers. Nonetheless, from the observations made, a working hypothesis on the data available has been developed. Assuming that this cross-linking occurs via the formation of ether linkages as shown in Figure 3, the following reactions in the cellulose can be predicted:

- 1) Rigidization with attendant ease of fracture;
- 2) Decrease in solubility as the molecular shape changes

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from a long extended form with readily accessible OH groups to a more spherical form with reduced surface area and inaccessible OH groups;

- 3) A rapid decrease in molecular weight or DP as the reactive glycoside linkages are cleaved, followed by a slowing of the decrease in DP as cross-linking takes place; and,
- 4) A decrease in the quantity of retained HCl as the process temperature is increased. The ether cross-links are thought to be formed by the reaction of OH groups with chlorinated cellulose, and the subsequent loss of HCl. Higher process temperatures should lead to more complete cross-linking and loss of HCl.

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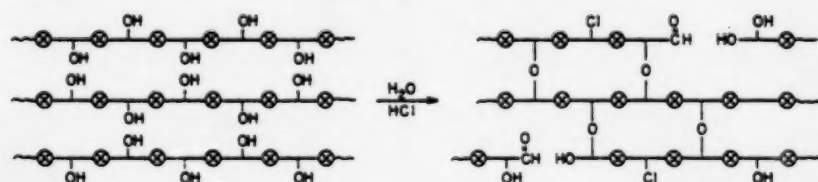


Figure 3. Possible embrittlement mechanism; hydrolysis and Cross-linking of adjacent cellulose chains by oxygen bridges.

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SECTION 4

POWDER PREPARATION

A major emphasis of this project was the production of large quantities of powder from RDF for combustion analysis. About 453.6 kg (1000 lb) of RDF were obtained from the Americology Resource Recovery Plant in Milwaukee, Wisconsin to be used as the feedstock for the embrittlement treatments. During the course of the project some 363 kg (800 lb) of RDF were processed in the UDRI Pilot Reactor Unit for the production of 252 kg (555 lb) of minus 149 μ (100 mesh) powder for testing and evaluation.

Batches of 2.3 kg (5 lb) of the RDF were embrittled in the reactor unit at a treatment temperature of 149°C (300°F) using a 72 percent hydrogen chloride, 28 percent nitrogen reactant gas mixture for treatment times of 3-5 min. The embrittled RDF was ball milled for two hours and then screened in a sieve stack for one hour. A tabulation of the powder preparation conditions is presented in Table 2.

TABLE 2. POWDER PROCESSING CONDITIONS

Quantity of RDF processed	2.3 kg (5 lb)
Processing temperature	149°C (300°F)
Processing time	3 - 5 min
HCl flow rate	439 cm ³ /sec (0.93 ft ³ /min)
N ₂ flow rate	170 cm ³ /sec (0.36 ft ³ /min)
HCl adsorbed by RDF	2% by wt
Ball mill time	2 hr
Screening time	1 hr

The reactor unit (shown in Figures 4 and 5), built by the University of Dayton Research Institute (UDRI), was designed to process 1.1 to 2.3 kg (2.5 to 5 lb) of shredded waste (newsprint or RDF) samples with a continuous flow of reactant gases. The interior of the reactor was constructed from a 113.6 l (30 gal)

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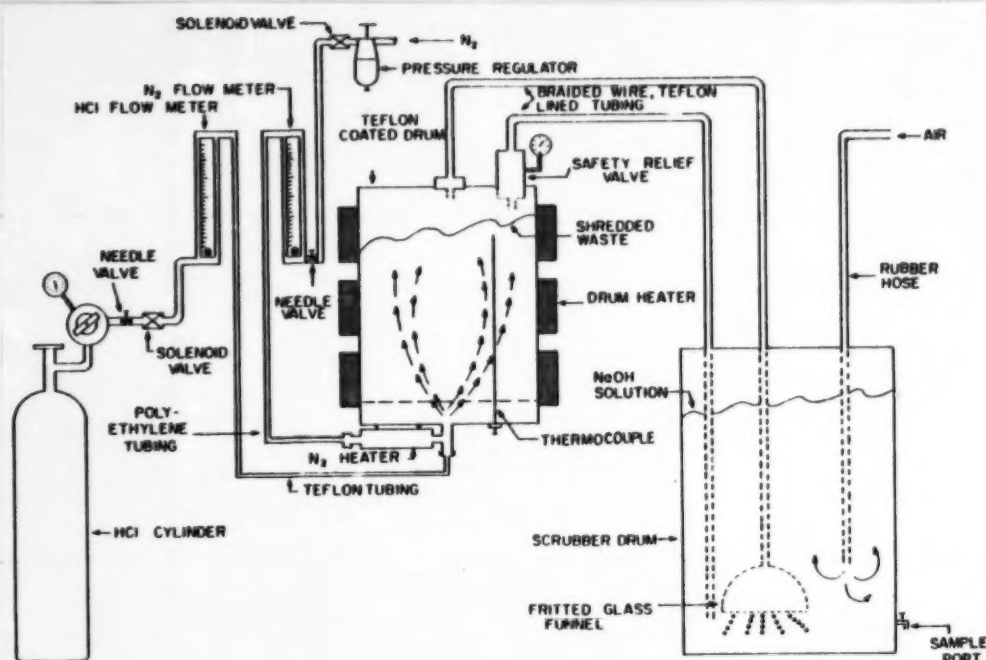


Figure 4. Process flow diagram for pilot reactor.

carbon steel drum coated with a 20 mil thickness of Emralon^{*} 314 (50% Teflon - 50% epoxy). The reactor is supported in a unistrut frame such that it could be loaded and unloaded by tilting it about a horizontal axis between two vertical unistrut channels. The shredded waste was introduced at the top and the lid was sealed with a specially designed silicone rubber gasket and locking ring to prevent leakage. Three 1800 watt drum heaters were installed on the outside of the reactor for heating. A stainless steel screen with 0.84 cm (0.33 in) diameter holes was installed on the lid to provide safety from excessive pressures. All temperature measurements were made with a digital thermometer.

Hydrogen chloride was supplied from a 27.2 kg (60 lb) HCl cylinder, and N₂ was drawn from an existing N₂ cylinder bank. A 5 kW heater was used to heat the N₂. Two glass rotameters, 0-99.1 l/min (0-3.5 ft/min) were used to measure the rate of the reactant gases flowing through the reactor.

The scrubber unit consisted of a polyvinyl chloride-lined 208.2 l (55 gal) drum containing 84 l (22.2 gal) of 0.15N sodium hydroxide solution. The unreacted gases were dispersed through a 15.2 cm (6 in) diameter fritted glass funnel into the NaOH

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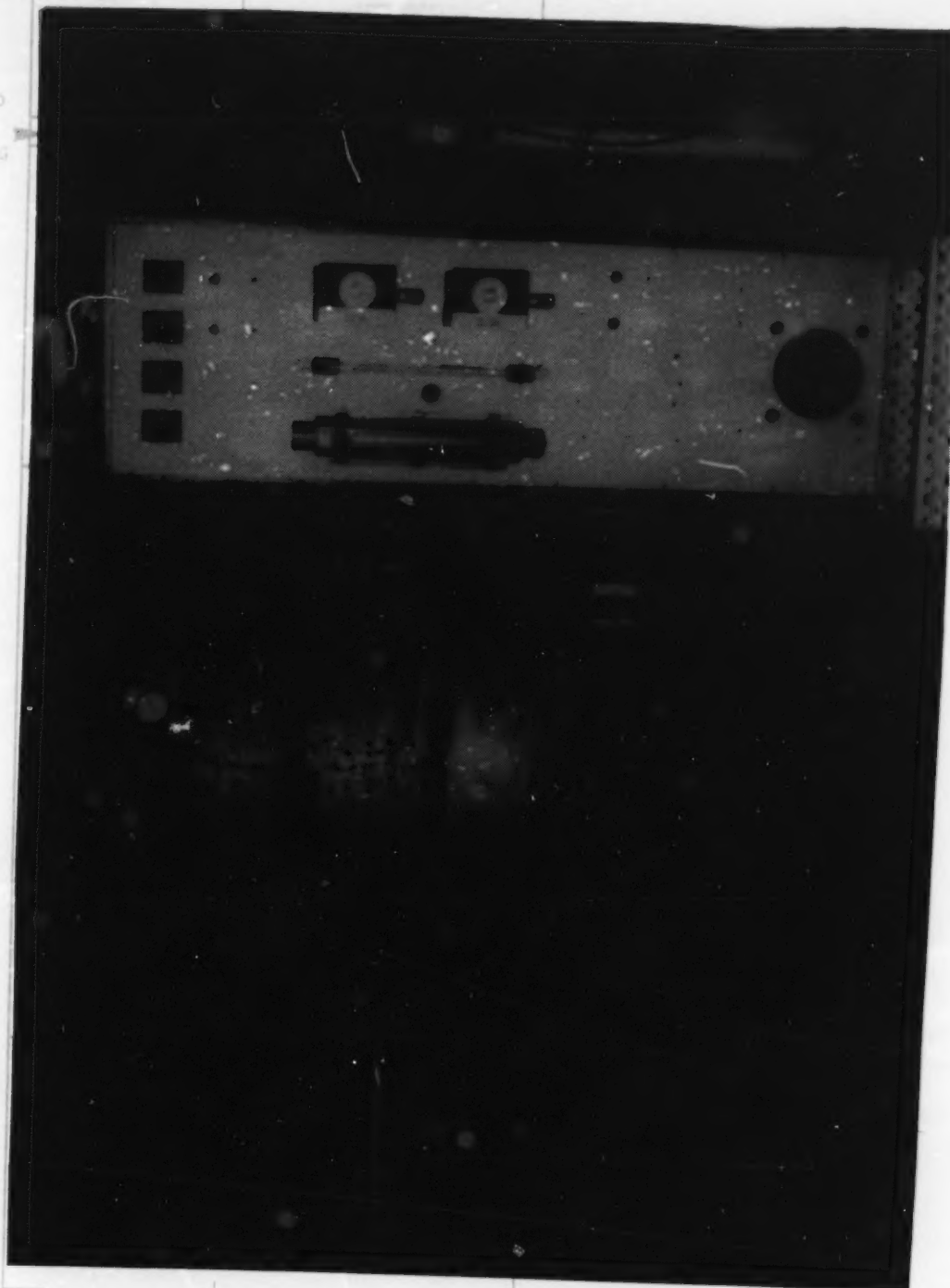


Figure 5. Pilot reactor.

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solution. Efficiency of the scrubber was tested by introducing a known quantity of HCl, and titrating a 10 ml (0.34 oz) sample from a 500 ml (16.9 oz) aliquot of the scrubber solution with 0.1N HCl. A series of tests showed that the titrimetric data could account for approximately 95% of the quantity of HCl calculated from flow measurements.

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After the reactor was charged with 1.1 kg (2.5 lb) of shredded waste, it was sealed and heated to the desired temperature with the drum heaters. Upon reaching the specified temperature, a moderate flow of HCl and N₂ was begun. The HCl flow was maintained for 3 to 5 minutes to provide the desired quantity of this reactant. The reactor was then purged with N₂ for an additional 0.5 hr. Gas flow rates and times were recorded from the control panel. Unreacted HCl and the N₂ passed out the top of the reactor through a 1.9 cm (0.75 in) Teflon lined tube and into the scrubber unit described above. Two aliquots of the scrubber solution were titrated with 0.1N HCl to account for the amount of unreacted HCl. The input to the reactor was calculated from the flow rate of HCl at the measured pressure and temperature. Output of HCl from the reactor was calculated from the change in normality of the NaOH solution. The retention of HCl could be determined by the difference in these two values.

After chemical treatment, the shredded waste was ball milled for 2 hrs. The ball mill unit consisted of a 12.3 l (13 qt) ceramic jar filled with 13.6 kg (30 lb) of 1.3 cm (0.5 in) x 1.3 cm (0.5 in) ceramic cylindrical grinding pellets. The jar was rotated on a pair of 5.1 cm (2 in) diameter hard rubber rollers, one of which was chain driven by a 186.4 watt (0.25 hp) electric motor. The ball milled powder was then screened through a stack of sieves for one hour. The screens used were built on wooden frames 0.37 m² (4 ft²). The screens had a capacity to process 0.9 kg/hr (2 lb/hr). Five screens were built having screen size openings of 0.64 cm (0.25 in), 354 μ (45 mesh), 149 μ (100 mesh) 74 μ (200 mesh), and a bottom pan. For the analysis of the powder, a RoTap shaker was used for a quartered sample (50 g) of powder. All of the minus 149 μ (100 mesh) material prepared was used for the evaluation and testing program.

During powder production, unpleasant odors and a significant quantity of sewer flies were generated from the stored RDF. The powder processing procedures also resulted in the generation of considerable amounts of dust, and it was necessary for the employees to wear dust masks and rubber gloves. The dust generated during the processing phase also raised concerns about the explosion hazards associated with the production of the powder.

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SECTION 5

POWDER CHARACTERIZATION

Samples of the powder produced were obtained throughout the program for chemical, physical, and thermal analysis. In addition, samples were sent to the Commercial Testing and Engineering Company and Battelle Columbus Laboratory for analysis of selected chemical and thermal properties.

Physical and Chemical Analysis

Particle size distribution, moisture content, morphology and density of the powder samples were measured to better characterize the physical nature of the powder. The particle size distribution was measured using a RoTap with quartered powder samples and the results are shown in Table 3. The data presented include the moisture content measured for each size fraction. All of the data reported represent the average values calculated from five or more measurements.

TABLE 3. PARTICLE SIZE DISTRIBUTION AND MOISTURE CONTENT OF POWDERED RDF

Particle Size μ (mesh)	Quantity %	Moisture %
+354 (+45)	18.1	5.86
-354 + 149 (-45+100)	12.5	6.54
-149 + 74 (-100+200)	31.1	5.91
-74 (-200)	<u>38.3</u>	5.03
	100	

Using a scanning electron microscope, the morphology of the minus 149 μ and 74 μ (100 and 200 mesh) powder were studied. Representative electron micrographs are shown in Figures 6 through 11.

The density of the loose powder, lightly compacted, and compressed has also been measured. The loose density of the minus 149 μ (-100 mesh) RDF powder was measured by filling a 50 milliliter graduated glass cylinder with powder to a defined volume and then weighing the cylinder contents. The cylinder was then

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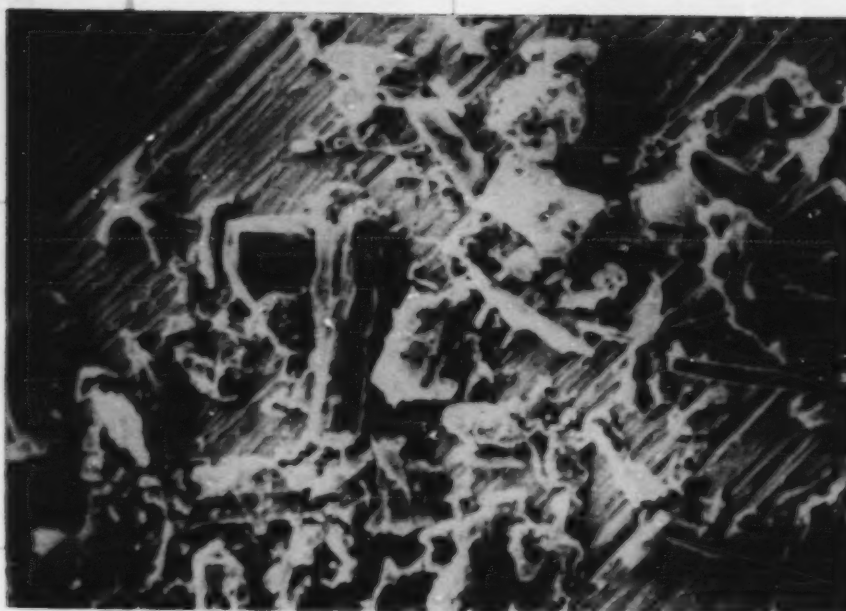


Figure 6. 149μ (100 mesh) material at 100X.

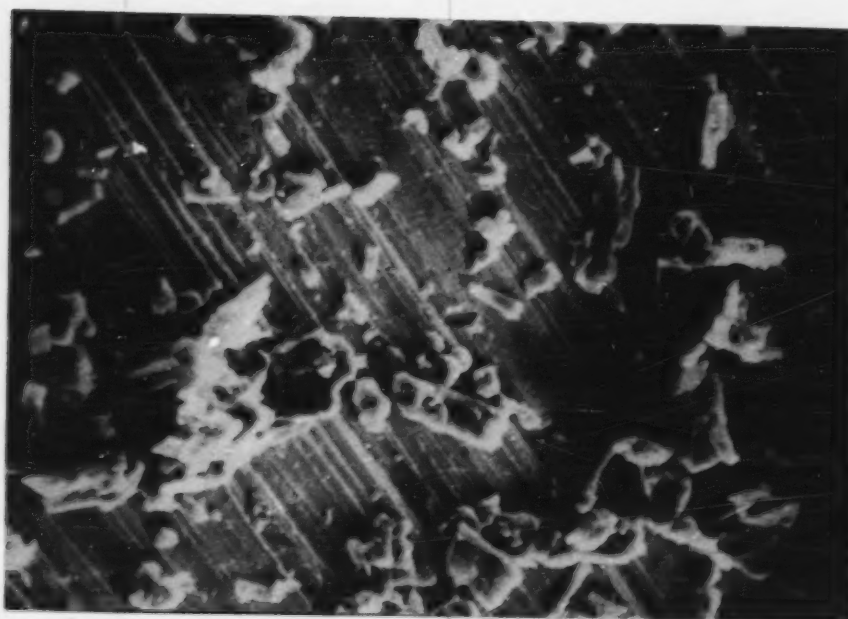


Figure 7. 74μ (200 mesh) material at 100X.

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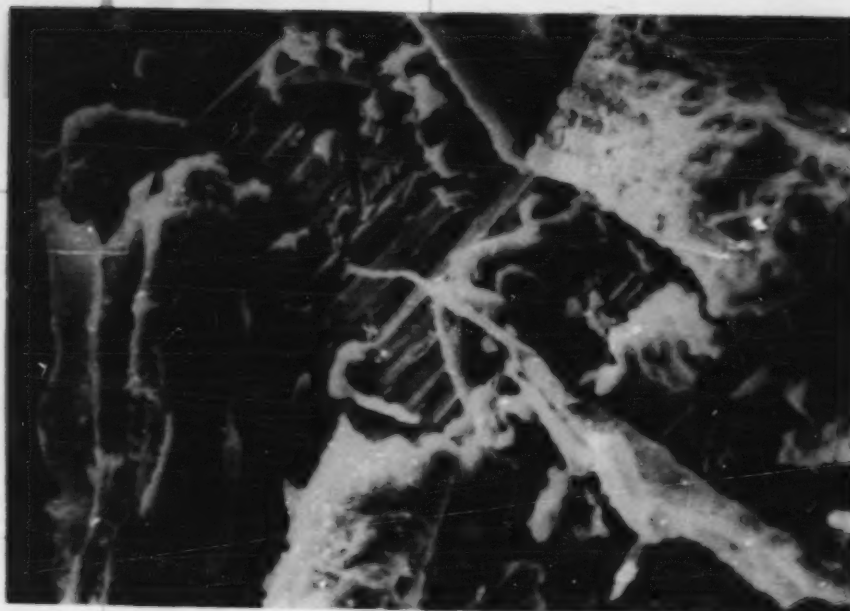


Figure 8. 149μ (100 mesh) material at 300X.

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Figure 9. 74μ (200 mesh) material at 300X.

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Figure 10. 149 μ (100 mesh) particle at 300X.

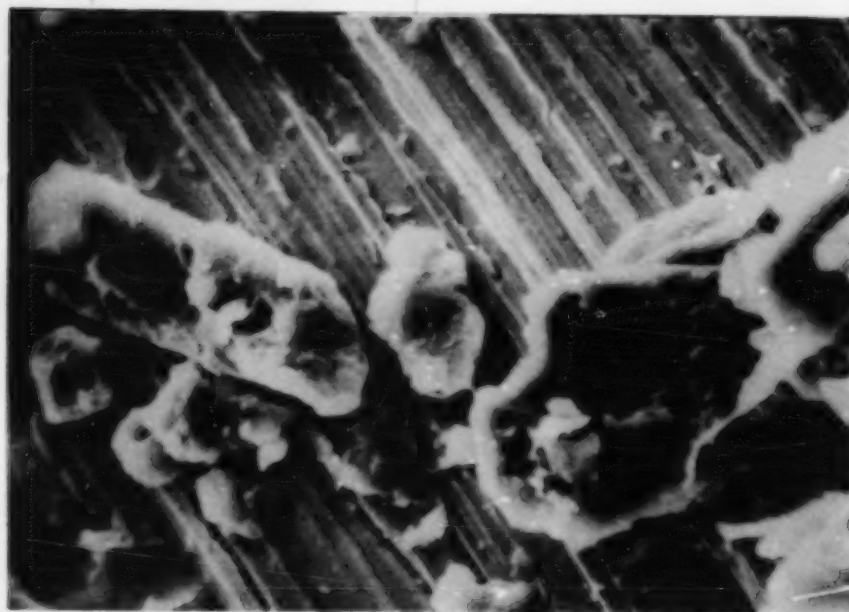


Figure 11. 74 μ (200 mesh) particles at 500X.

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gently tapped to remove air gaps, more powder was added to maintain the same volume and the new weight determined. The compressed density of the powder was determined by pressing 1.5 g (0.053 oz) of powder in a cylindrical die with a hydraulic press to $1.55 \times 10^6 \text{ kg/m}^2$ (2200 psig). Using this procedure, several 1.27 cm x 1.27 cm (0.5 in x 0.5 in) cylindrical pellets were made and the average density of the pellets was measured. The results of the density measurements are reported in Table 4. The data show that a 400 percent increase in density was obtained when loosely packed powder was compressed to a pellet.

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TABLE 4. DENSITY OF MINUS 149 μ (-100 Mesh) POWDER[†]

Condition	kg/m ³	(lb/ft ³)
Loosely packed	271	(16.9)
Compact	418	(26.1)
Compressed	1096	(68.4)

Chemical properties of the powder were measured at both the UDRI and the Commercial Testing and Engineering Company, Chicago, Illinois. Proximate and ultimate analysis, mineral analysis, and fusion temperature of the ash in the powder were measured by the Commercial Testing and Engineering Company and the results are presented in Tables 5 through 8. The average ash content of the powder reported by the Commercial Testing and Engineering Company was considerably lower than that reported by Battelle in its combustion studies (Table 5 vs. Table 9). Therefore, a number of ash analyses were conducted by the UDRI on several different size fractions of powder using ASTM standard D271. The results obtained are presented in Table 9. As shown in Table 9 almost 40 percent of the minus 345 μ (-45 mesh) powder from the ball mill is noncombustible. The higher ash content found in the minus 74 μ (-200 mesh) fraction indicates that the finer fraction of the powder contains a greater fraction of inert materials believed to be predominantly glass particles.

Comparison of the ash characteristics of RDF powder and coal showed that the SiO₂ is in the usual coal-ash range but the Al₂O₃ is very low. Most coals have a SiO₂/Al₂O₃ ratio greater than 2. The Fe₂O₃ found in the RDF ash was very low. Ash from some coals, can contain as much as 40 percent Fe₂O₃. The CaO and MgO content of the RDF ash was high, but comparable to some Western low-rank coals. The Na₂O content of the RDF ash was also high, but in the range of many lignites. Bituminous coals seldom exceed 0.3 percent total Na₂O + K₂O in the dry coal; while the RDF powder contains 2.26 percent. Sulfur in the RDF powder is very low, hence emission of SO₂ will be only 0.74 lb/10⁶ BTU. The potential

*tests conducted at UDRI

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TABLE 5. PROXIMATE ANALYSIS⁺

Property	Powdered RDF (%)		Midwestern Coal (%)	
	<u>As Recv'd</u>	<u>Dry Basis</u>	<u>As Recv'd</u>	<u>Dry Basis</u>
Moisture	7.33	xxxxx	11.07	xxxxx
Ash	24.91	26.98	12.26	13.79
Volatile	51.83	55.93	34.96	39.31
Fixed Carbon	15.93	17.19	41.71	46.90
	100.00	100.00	100.00	100.00

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TABLE 6. ULTIMATE ANALYSIS⁺

Property	Powdered RDF (%)		Midwestern Coal (%)	
	<u>As Recv'd</u>	<u>Dry Basis</u>	<u>As Recv'd</u>	<u>Dry Basis</u>
Moisture	7.33	xxxxx	11.07	xxxxx
Carbon	32.70	35.29	59.49	66.89
Hydrogen	4.30	4.64	4.15	4.67
Nitrogen	0.68	0.73	0.92	1.04
Chlorine	3.11	3.36	0.16	0.18
Sulfur	0.20	0.22	4.39	4.94
Ash	24.91	26.88	12.26	13.79
Oxygen	26.77	28.88	7.56	8.49
	100.00	100.00	100.00	100.00

TABLE 7. FUSION TEMPERATURE OF ASH⁺

Property	Powdered RDF °C(°F)		Midwestern Coal °C(°F)	
	<u>Reducing</u>	<u>Oxidizing</u>	<u>Reducing</u>	<u>Oxidizing</u>
Initial De-formation	1065(1950)	1100(2010)	1093(2000)	1260(2300)
Softening Point	1218(2220)	1222(2230)	1182(2160)	1332(2430)
Hemispherical	1238(2260)	1250(2280)	1193(2180)	1343(2450)
Fluid, Tem-perature	1318(2400)	1360(2480)	1271(2320)	1432(2610)

⁺Data from Commercial Testing and Engineering Company

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TABLE 8. ASH ANALYSIS⁺

Mineral	Powdered RDF % Weight, Ignited	Midwestern Coal % Weight, Ignited
Silica, SiO ₂	56.40	47.52
Alumina, Al ₂ O ₃	9.55	17.87
Titania, TiO ₂	1.10	0.78
Ferric, Oxide, Fe ₂ O ₃	3.17	20.13
Lime, CaO	12.50	5.75
Magnesia, MgO	6.30	1.02
Potassium Oxide, K ₂ O	1.50	0.36
Sodium Oxide, Na ₂ O	6.88	1.77
Sulfur Trioxide, SO ₃	1.92	--
Phos. Pent. P ₂ O ₅	0.30	--
Undetermined	0.38	4.8
Silica Value	71.97	63.85
Base/Acid	0.45	0.44
T ₂₅₀ /Poises	1291°C (2355°F)	1299°C (2370°F)

TABLE 9. ASH DISTRIBUTION IN RDF POWDER*

Particle Size μ (mesh)	Quantity %	Ash % of Fine Fraction
+354 (+45)	18.1	-
-354 + 149 (-45 + 100)	12.5	35.1
-354 + 74 (-100 + 200)	31.1	37.5
-74 (-200)	38.3	43.6

⁺Commercial Testing and Engineering Company

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pickup of SO₂ by the alkalis in the ash could further drop the SO₂ emission level to about 0.6 lb SO₂/10⁶ BTU under good conditions.

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The RDF ash flow properties are estimated to be moderate, and are not likely to form much slag during combustion unless the furnace temperatures are high. However, some problems with slag deposits on tube banks such as superheaters and reheaters can be expected. Coal ash has a somewhat lower viscosity compared to the ash from RDF powder, and less slagging problems are encountered. Burning RDF powder with midwestern coal will raise the combined ash viscosity appreciably; however, small amounts of RDF powder (less than 20 percent) will have little effect on the characteristic of the resultant ash.

It can be anticipated that the high chlorine content of the powder (3.36 percent) is likely to also lead to corrosion problems in the heat exchangers downstream of the furnace, particularly in the air heaters. Further, when mixed with coal, it is expected that trisulfates will not be formed under the slag on the furnace wall tubes because the CaO and MgO in the RDF ash total 18.8 percent.

Generally, the RDF ash does not differ substantially from ash found in many other solid fuels. Except for the high chlorine and sodium levels, the ash from the RDF powder should not be particularly troublesome when the RDF powder is burned with pulverized bituminous coal in large utility boiler furnaces. Little real data are available on the potential chlorine and sodium problems in operating furnaces with RDF; however, considerable interest is being expressed today in these problems.⁽⁶⁾

The RDF powder can be characterized by its physical and chemical properties. Almost 70 percent of the powder is minus 149 μ (100 mesh) and the average moisture content is 5.5 percent. The average heat content was measured at about 13,025 MJ/kg (5600 BTU/lb). Most of the powder particles appear as short, choppy fibers, dispersed in the fibrous mix as irregular shaped particles which were found by Energy Dispersive X-ray Analysis (EDXA) to be predominantly alumina silicate glasses. Comparing the RDF powder with bituminous coal, it can be seen from the proximate analysis that the RDF powder has approximately 15 percent more ash, 15 percent more volatile materials, and 30 percent less fixed carbon than that reported for coal. The ultimate analysis shows that the RDF powder has about half the total carbon content of that reported for coal. It should also be noted that although the RDF powder has a considerably higher chlorine content, most coal has a considerably higher sulfur content. The total sulfur and chlorine content of the two materials are essentially equivalent indicating similar contamination and corrosion problems. However, more recently the stringent air pollution codes have caused utilities to use lower sulfur coals for combustion. Because the RDF powder is more volatile than bituminous

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coal, it is reasonable to assume that the RDF powder is likely to be more explosive than coal powder and extra precautions may be necessary for the safe handling of the powdered RDF material. Suspension of the powdered RDF in an oil slurry could be one means of safely transporting and utilizing the powdered RDF material.

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Thermal Analysis

The heat content of the powder was measured at the UDRI and the Commercial Testing and Engineering Company. At the UDRI the heat content was measured using 1 gm (0.035 oz) samples in a Parr Adiabatic Bomb Calorimeter following ASTM D2015. The results obtained are presented in Table 10.

TABLE 10. HEAT CONTENT OF RDF POWDER⁺

Particle Size μ (mesh)	Heat Content as Received Mj/kg (BTU/lb)	Heat Content Dry Mj/kg (BTU/lb)
-0.64cm (-1/4 in)	13,255 (5699)	13,428 (5773)
+354 - 0.64cm (+45 - 1/4 in)	14,883 (6399)	- -
+354 + 149 (-45 + 100)	13,632 (5861)	14,658 (6302)
-149 + 74 (-100 + 200)	13,132 (5646)	13,198 (5674)
-74 (-200)	13,060 (5615)	13,777 (5923)
Average -354 μ (-45 Mesh)	13,274 (5707)	13,877 (5966)
Commercial Testing & Engineering Co. data	12,846 (5523)	13,863 (5960)

Thermogravimetric (TGA) and Differential Thermal Analysis (DTA) methods were used to further evaluate the thermal properties of the RDF powder. These studies were conducted by Battelle Columbus Laboratory.

Thermograms from these analytical methods are presented in Figures 12, 12, and 14. Figures 12 and 13 show the data obtained from the TGA method; Figure 14 is the thermogram from the DTA method. A summary of the data from the thermograms is presented in Table 11 along with comparative data for a bituminous coal.

The RDF thermogram in Figure 12 is a presentation of the percent sample remaining versus temperature. Comparing the data from this thermogram with the data for a bituminous coal summarized in Table 11 shows that:

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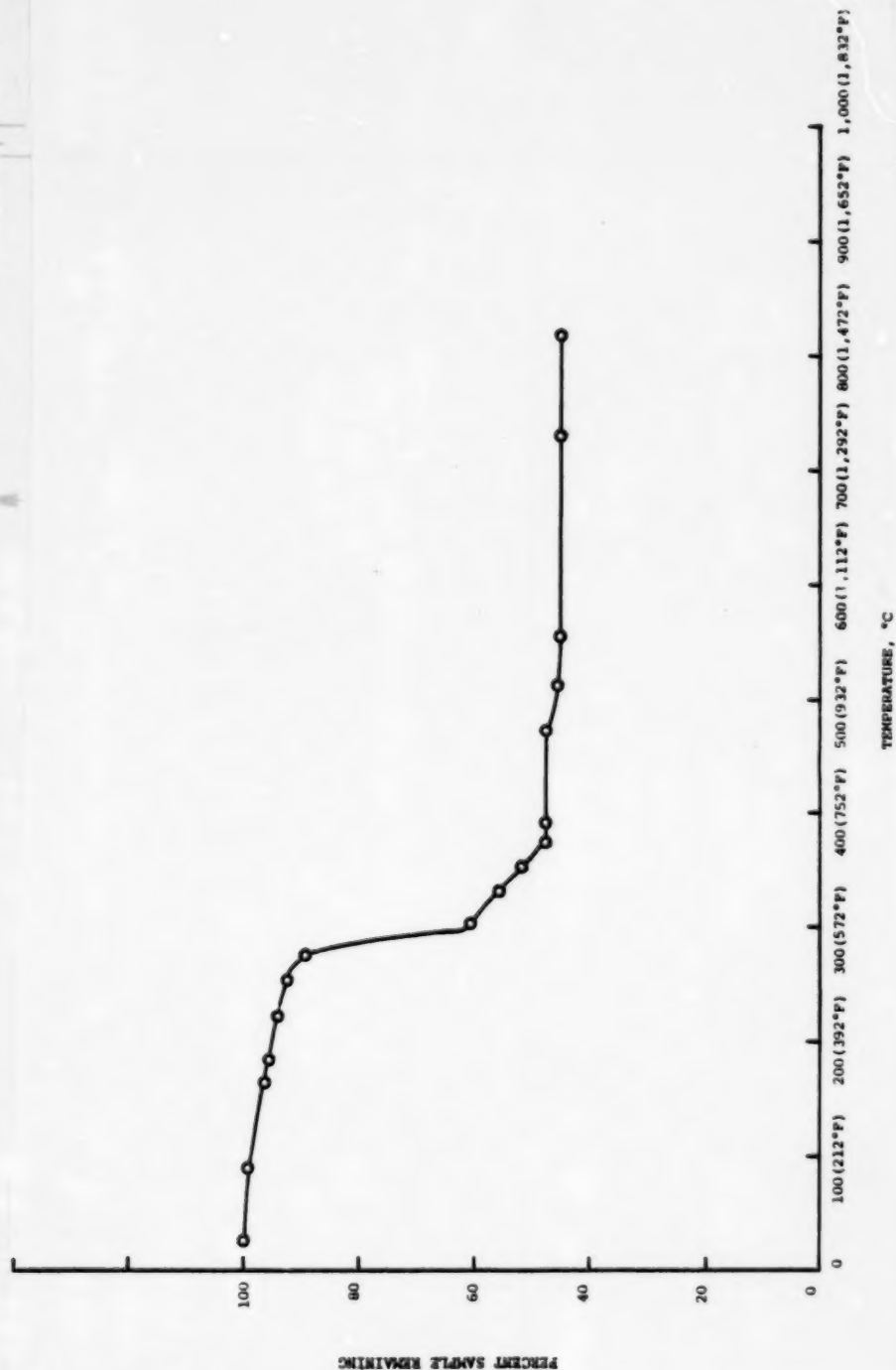


Figure 12. Thermogram of RDF powder fuel at 15°/min heating rate in air⁺

⁺Battelle Columbus

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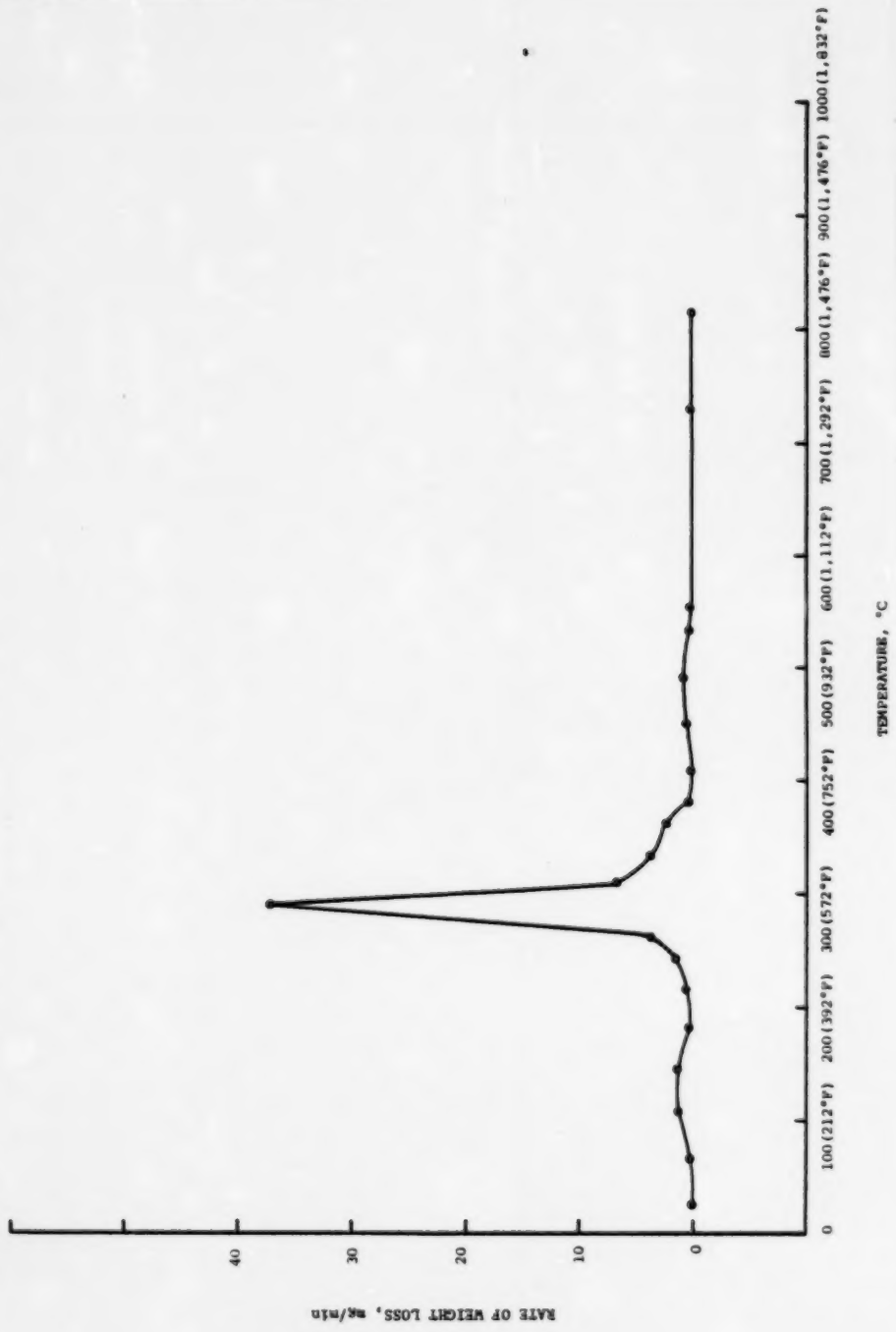


Figure 13. Burning profile of RDF powder fuel at 15°/min heating rate in air.[†]

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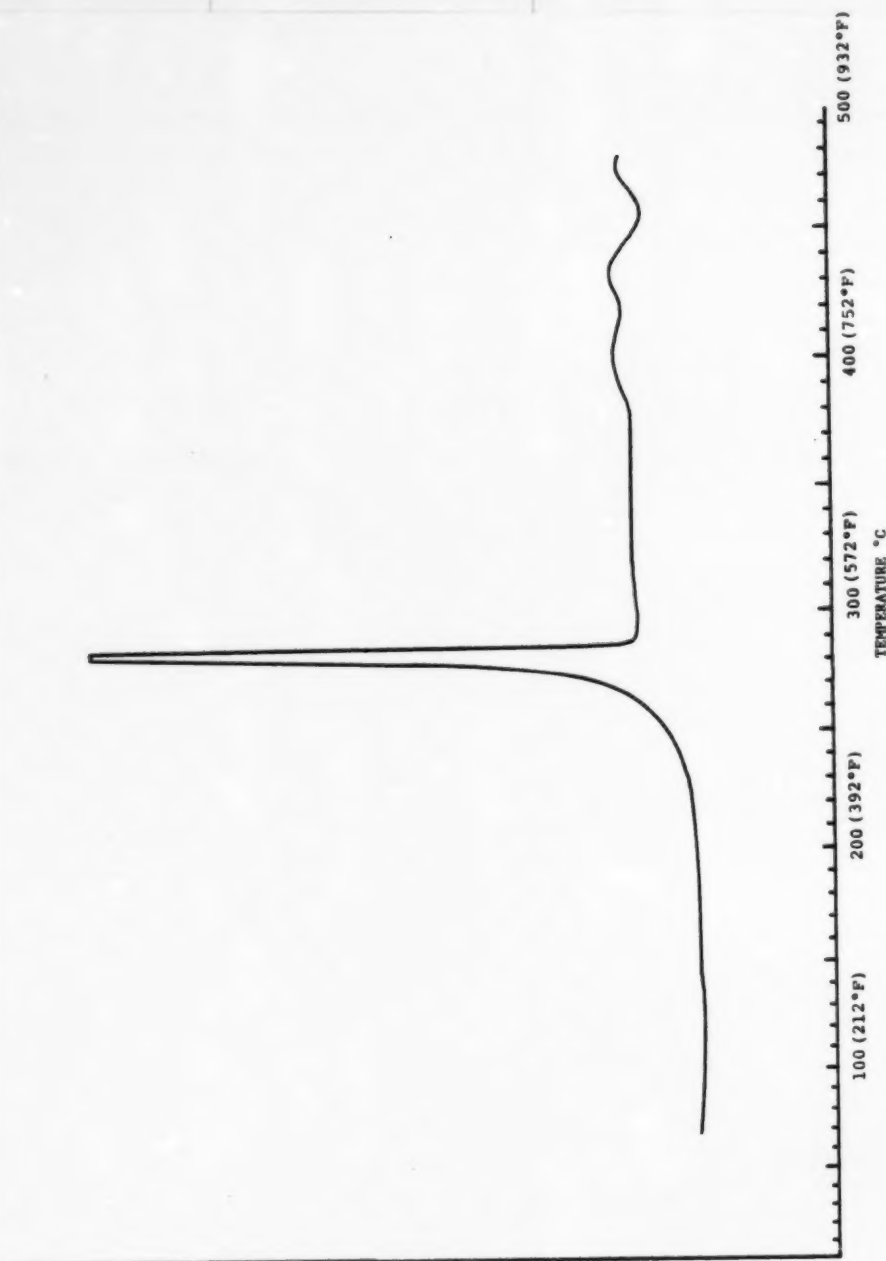


Figure 14. DTA plot[†]

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TABLE 11. THERMAL ANALYSIS OF POWDERED RDF⁺

Thermogravimetric Analysis (a)

Property	Powder RDF	Coal
Ash %	44.4 (e)	10.3
Temperature Range (b) (°C)	130-380 (266°-716°F)	220-585 (428°-1085°F)
Maximum Rate of Weight Loss (mg/min)	37 (81.6 x 10 ⁻⁶ lb/min)	17.5 (38.6 x 10 ⁻⁶ lb/min)
Temperature at Maximum Rate of Weight Loss (°C)	290 (554°F)	320 (608°F)

Differential Thermal Analysis (c)

Starting Exotherm (°C)	222 (431°F)	233 (451°F)
Ignition Point (°C)	276 (529°F)	426 (799°F)
End of Ignition Exotherm (°C)	289 (552°F)	615 (1139°F)
Secondary Exotherms (°C)	379-433 (714°- 811°F)	-----
Endotherm (°C)	457 (855°F)	400-584 (752°- 1082°F) (d)

(a) TGA performed with Cahn Electrobalance at 15°C/min (59°F/min) and air flow of 800 ml/min (.0035 gal/sec)

(b) Temperature range over which most of weight loss occurs

(c) DTA performed with Stone Model 202 at 15°C/min (59°F/min) and dynamic gas flow of 0.0057 m³/hr (0.2 SCFH)

(d) Endotherm range in presence of N₂ gas. Three peaks in each range

(e) Residue measured after combustion in the test burner

⁺Battelle Columbus Laboratory, data from Figures 12, 13 and 14

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(1) The RDF powder contains a significantly higher percentage of ash than that found in typical high ash coal (more than double the average coal). However, there is a large discrepancy between the ash content measured in the TGA method and that found by the proximate-ultimate analysis performed by Commercial Testing and Engineering Company (44.4% versus 24.9%). A possible explanation may be that the few hundred milligrams of RDF powder used in the TGA method is not representative of the bulk material.

(2) The temperature range over which most of the weight loss occurred was considerably lower for the RDF powder than for the coal: 130°C - 380°C (266°F - 716°F) for the RDF compared to 220°C - 585°C (428°F - 1085°F) for coal. The RDF powder appears to be composed of more easily volatilized and/or oxidized components than are found in coal.

(3) The primary ignition exotherm for the RDF powder is completed at a much lower temperature than observed for the coal, 289°C (552°F) for the RDF compared to 615°C (1139°F) for the coal. The fuel components in the RDF powder are thus more easily burned than those in the raw coals. Two small secondary exotherms were observed for the RDF powder at 379°C (714°F) and 433°C (811°F), however, these are well below the temperatures observed at the end of the ignition exotherm for the coal.

(4) Endotherms occur at comparable temperatures for both the RDF powder and the coal. However, the endothermic reactions in both fuel types are minor compared to the reactions evolving heat.

Data from the TG and DT analyses of the RDF powder indicate that the RDF powder is more easily ignited than coal and combustion of the RDF powder is completed at temperatures lower than that reported for the coal. It is expected that the RDF powder would burn more easily than coal. However, the high ash content found in the RDF powder could present a number of processing problems. For example, considerably higher feed rates of RDF would be required to maintain equivalent heating rates compared to most coals. Ash handling problems would also be aggravated considerably in burning the RDF powder. However, it should be noted that the use of an RDF feedstock from a refuse processing plant designed to minimize the glass content (by screening, or other processes) would reduce these problems.

It would appear that the main areas of concern in burning the RDF powder (aside from corrosion and fouling problems to be discussed later) would be with powder feeding and ash handling equipment at the combustion facility. It is anticipated that these problems would be reduced considerably if the RDF powder were co-fired with coal.

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SECTION 6

POWDER/OIL SLURRIES

Suspension of the RDF powder in a fuel oil offers a number of advantages for extending the commercial potential of the RDF powder. Powder/oil suspensions should be easier to transport and less subject to explosions. In addition, suspension of the powder in oil should facilitate introduction of the powder into conventional oil fired boiler and furnace units.

During the course of this program two different techniques for preparing powder/oil slurries were investigated and selected properties of the slurries prepared were evaluated. The two methods investigated were:

(a) gradual dispersal of minus 149 μ (-100 mesh) powder in diesel oil by conventional blending procedures; and

(b) combined ball milling and mixing of the treated RDF with diesel oil.

However, the slurries prepared by both methods did not display long term stability. Within 8 hours the powder was found to have completely settled out of the diesel oil. Dispersion agents were investigated for enhanced slurry stabilization. Slurries of 23 and 37 weight percent solids were prepared to evaluate settling characteristics, density, viscosity and combustion characteristics.

SLURRY PREPARATION

Direct Dispersion of Powder in Oil

Several 150 ml (40×10^{-3} gal) slurry samples with 37 percent by weight powder were prepared. The slurries were prepared by gradually mixing 50g (1.8 oz) of minus 149 μ (-100 mesh) RDF powder in 100 ml (26×10^{-3} gal) of diesel oil with a magnetic stirrer until uniform suspension was obtained. The blended slurry which appeared black in color was fairly thick and of uniform consistency.

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Combined Ball Milling and Slurry Preparation

The concept of ball milling the treated RDF in diesel oil appears to be an attractive method of preparing the powder/oil slurries. In an effort to investigate this concept, a 250 g (8.8 oz) sample of treated RDF was ball milled in a 12.3 l (13 qt) jar mill with 1,000 ml (0.26 gal) of diesel oil. The ratio of treated RDF to diesel oil was determined by a series of experiments using a number of different compositional ratios. From this series of tests it was found that 23 weight percent RDF in oil provided the best results.

After 2.5 hours of ball milling the oil slurry was filtered through a 0.64 cm (0.25 in) screen to separate the nongrindables (mostly plastics), which would inhibit effective fluid transport from the slurry. The appearance of the milled slurry was very similar to that obtained by adding the RDF powder to the diesel oil. One advantage of preparing powder/oil slurries by this method is that more powder is retained in the slurry which would otherwise be lost as either coarse rejects or dust during the conventional powder slurry preparation processes. It also appears that by employing this process, dust problems can be minimized and consequently the risk of dust explosion is reduced. However, this is an area which requires further study.

Slurry Stabilization

Colloidal dispersion in oil consists of discrete particles held in suspension due either to their affinity for oil (oleophilic colloid) or to surface electric charges on the particles (oleophobic). Since cellulose particles are not soluble in the oil, it is believed that the RDF powder/oil slurry is essentially an oleophobic suspension with electrostatic repulsion between the charged colloidal particles resulting in the development of a stable suspension.

Particle size of the powder is one of the most significant properties for obtaining stable colloidal dispersions in the oil. With larger particles the ratio of surface area to mass is low and mass effects such as sedimentation by gravity forces predominate. For the smaller particles the surface area to mass ratio is high and surface phenomena, like electrostatic repulsion, become significant.

A colloidal suspension of RDF powder in diesel oil can be stabilized either by selecting an oil which would have a density compatible with the density of the RDF powder or by the addition of a dispersing agent. It is also believed that by emulsifying water into diesel oil, the viscosity of the resulting mixture would be greater than pure diesel oil and have greater stability. From Stokes' law it can be seen that increased viscosity reduces particle settling rate.

In the preliminary studies to evaluate the stability of the

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powder/oil slurries, several samples of 37 weight percent powder were prepared. The slurries were produced by mixing 50 gm (1.8 oz) of minus 149 μ (-100 mesh) RDF powder in 100 ml (26×10^{-3} gal) of diesel oil. The blended slurries were placed in a hood and the sedimentation characteristics were observed. The sedimentation pattern for these slurries are analogous to zone settling where a zone is formed when rapidly settling coarser particles act as a group and collective settling occurs. When particle concentration reaches this point, a definite interface is formed between the settling particles and the fluid. For these initial evaluations the solid fluid interphase was recorded as a function of time and was used as the criterion to compare the stability of the different suspensions prepared. After 4 hours, the solid fluid interphase in the beaker was observed to have dropped approximately 100 ml (26×10^{-3} gal) with a clear layer of oil on top, indicating that almost all the particles had settled out.

In an effort to obtain more stable suspensions, various dosages of the dispersing agent, Rheotol (manufactured by R. T. Vanderbilt) were added to the newly prepared slurry samples and the solid fluid interphase readings were recorded every four hours. These tests showed that 1 ml ($.26 \times 10^{-3}$ gal) of Rheotol in a 100 ml (26×10^{-3} gal) slurry was the minimum quantity of dispersing agent required to achieve satisfactory stable suspensions. After four hours of settling the solid fluid interphase dropped only 25 ml (6.6×10^{-3} gal). After 20 hours the interphase had dropped 100 ml (26×10^{-3} gal) for complete settling with a discolored yellow layer of oil on top indicating that not all of the particles had settled out.

To investigate the effects of particle size on the sedimentation of the slurry, a 150 ml (39×10^{-3} gal) sample of 37 weight percent solids was prepared using minus 74 μ (-200 mesh) powder. After four hours, the interphase dropped 100 ml (26×10^{-3} gal) for complete settling. However, with the addition of Rheotol (1 % by volume), the suspension became more stable and after four hours the interphase had dropped only 15 ml (3.9×10^{-3} gal). After 20 hours, complete settling was observed with a discolored yellow layer of oil at the top indicating that not all of the solids had settled out.

The results of these preliminary slurry stability tests are summarized in Table 12. From the results, it appears that powder/oil slurries of both minus 149 μ (-100 mesh) and minus 74 μ (-200 mesh) powder settled rapidly (4 hr) without any significant differences in the settling characteristics. However, addition of a dispersing agent, Rheotol (1 percent by volume) resulted in the stabilization of slurries with powder of both sizes. Greater stability was observed in the slurries prepared from the minus 74 μ (-200 mesh) powder. It is believed that with further reduction in particle size, even more stable slurries could be obtained. Settling measurements were not made for the slurries

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TABLE 12. PRELIMINARY EVALUATION OF OIL-POWDER SLURRY

Particle Size μ (mesh)	Quantity of Pow- der in Slurry Wt %	Quantity of Slurry/ml ($\times 10^{-3}$ gal)	Quantity of Dis- persing Agent/ml ($\times 10^{-3}$ gal)	Settling Time hr	Settling Depth/ml ($\times 10^{-3}$ gal)
-149 (-100)	37	150 (40)	0	4	100 (26)
-149 (-100)	37	150 (40)	1.5 (.39)	4	25 (6.6)
-149 (-100)	37	150 (40)	1.5 (.39)	20	100 (26)
-74 (-200)	37	150 (40)	0 --	4	100 (26)
-74 (-200)	37	150 (40)	1.5 (.39)	4	15 (3.9)
-74 (-200)	37	150 (40)	1.5 (.39)	20	100 (26)

NOTE: Above screening was conducted in 250 ml (66×10^{-3} gal) beaker.

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prepared by combining the milling and blending process.

SLURRY CHARACTERIZATION

The apparent density and viscosity of powder/oil slurries were measured immediately after preparation and were compared with pure diesel oil. A Brookfield Viscometer (Model RVF 7) was used to measure the viscosities of the mixture and the pure diesel oil. Since the apparent viscosity of powder/oil mixture varies with shear rate, four determinations were made with number 1 spindle at 2, 4, 10, and 20 RPM. The averages of the four determinations are reported in Table 13. The preliminary results in Table 13 show that the density and viscosity of the oil is increased significantly (as expected) when the powder is dispersed in the oil. It is interesting to note that the density of the freshly made 37% by weight powder/oil slurry is approximately the same as water and should have interesting transport and storage characteristics.

TABLE 13. DENSITY AND VISCOSITY OF OIL AND POWDER/OIL SLURRY
[At 24°C (75°F) & 10,336 kg/m² (14.7 psia)]

	Diesel Oil	37% Powder/Oil Slurry
Density (ρ), g/cm ³ (oz/in ³)	0.8 (0.49)	1.01 (0.58)
Viscosity (μ), cp	10.62	32.00

NOTE: The Brookfield Viscometer Model #RVF7 with number 1 spindle was used for all viscosity measurements.

It should be noted that only preliminary slurry characterization studies have been conducted. Effective design of transportation and storage systems for the powder/oil slurry would require an extensive investigation of the flow and corrosion characteristics of the slurry.

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SECTION 7

INVESTIGATION OF THE BURNING CHARACTERISTICS OF THE POWDERED RDF COAL AND POWDER/OIL SLURRIES

RDF POWDER/COAL FIRINGS

The objective of this part of the study was to investigate the combustion characteristics of the RDF powder as a fuel. Combustion studies of the RDF powder and the RDF powder mixed with powdered coal were conducted.

Experimental Approach

RDF powder, powdered coal,⁺ and two RDF-coal mixtures were fired in Battelle's small pulverized coal combustor units. The fuel feeder and combustion unit used in this study are shown in Figure 15. Fuel is fed to the combustor by lifting the small particles from the solid fuel surface with air jets and entraining them in a 0.64 cm (0.25 in) O.D. tube, which leads to the burner head. With this arrangement, the combustor can burn pulverized coal at rates from 0.454 - 1.13 kg/hr (1 to 2.5 lb/hr) and can maintain maximum combustion temperatures approaching 1482°C (2700°F) for short periods of time and lower temperatures [1371°C (~2500°F)] for extended periods of time. When burning coal, this unit is mounted in a vertical position to minimize fly ash deposition along the after-cooler tube walls. The dry pulverized coal is transported to the combustor from a feeder by primary air. This primary air comprises about 1/3 of the total air required. The remaining (secondary) air can be introduced axially and/or tangentially to the combustor to produce varying amounts of turbulence and to alter flame shape. Gas residence time in the combustor chamber ranges from about 0.7 to well over 1.0 second depending on temperature conditions, fuel type, firing rate, and excess air level.

The flue gas components are cooled in the after-cooler section. There are sampling ports spaced at one foot intervals along the entire section of the after-cooler to measure gas temperature or gas constituents. Flue-gas samples are generally taken after the components have cooled below 260°C (500°F). This occurs toward the exit end of the after-cooler as indicated by the probe location shown in Figure 15. Other ports may be used

Illinois No. 6 Coal

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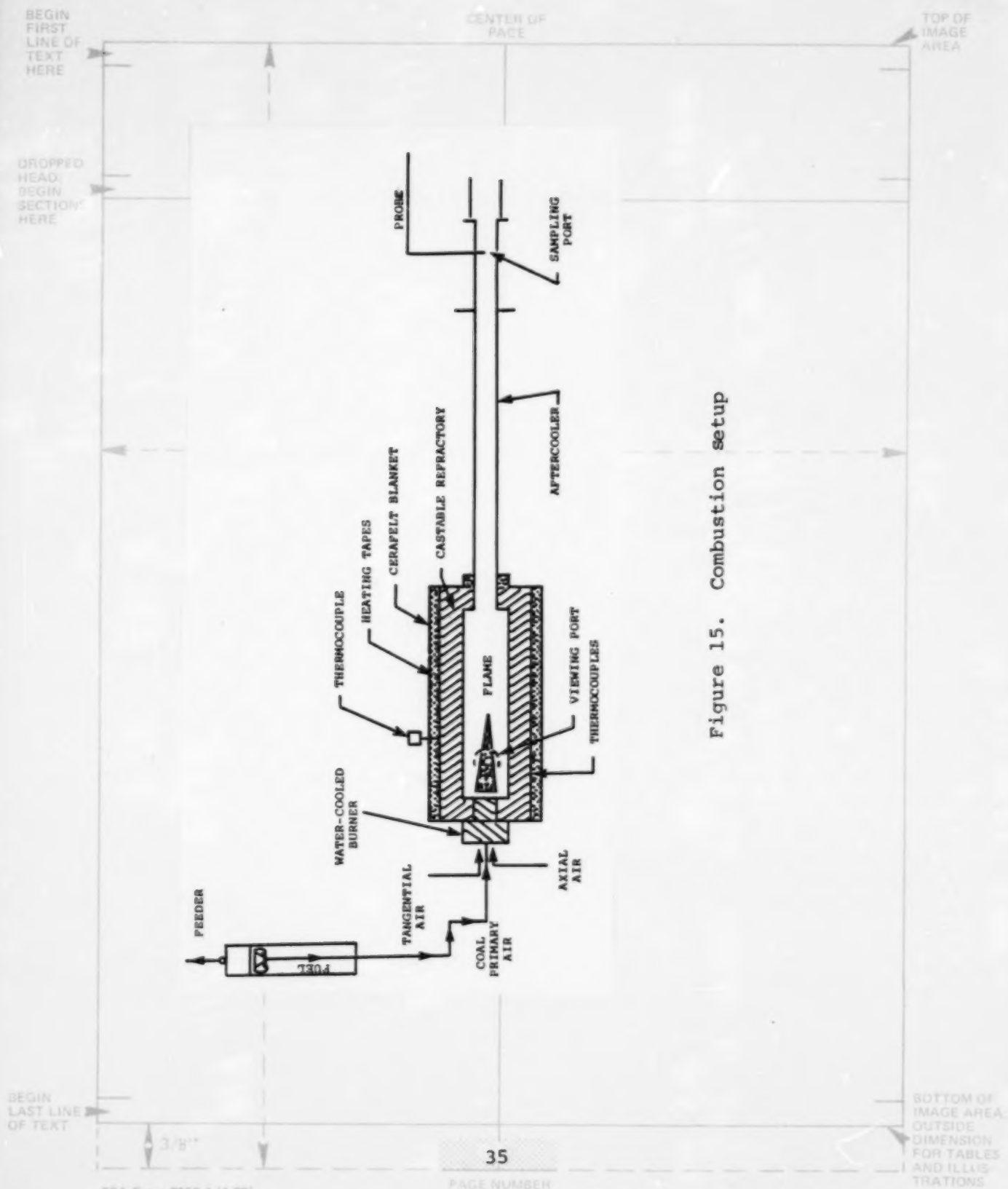


Figure 15. Combustion setup

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as needed.

Fuels

The fuels and fuel mixtures used in this study were as follows:

1. Illinois No. 6 coal⁺
2. RDF powder
3. 25 percent RDF; 75 percent coal (by weight)
4. 50 percent RDF; 50 percent coal (by weight)

The Illinois No. 6 coal was used as a reference coal. Proximate and ultimate analyses of the coal and the RDF used in this program were shown in Tables 5 and 6. Six combustion runs were conducted with the various fuel combinations. A compilation of the combustion runs and the results obtained are presented in Table 14.

As seen from the chemical analysis, the RDF powder has a higher percent of volatiles than the coal, which should aid combustion. However, it also has more ash and chlorine content than the coal, which is not very desirable for combustion processes. The chemical analysis also shows that oxygen (by difference) is also much higher in the RDF powder. The coal on the other hand has more carbon, a much higher sulfur level, and a heat content about twice that of the RDF powder. Measurements at the UDRI also indicate that the RDF powder density (Table 4) is about half that of coal. The lower density and heat content of the RDF powder is likely to present feeding problems in firing the powdered RDF.

Firing Conditions

The first four columns in Table 14 show the firing conditions used for each of the runs made with the combustor. Fuel feed rates from about 0.454 - 0.9 kg/hr (1 to 2 lb/hr) were used in the runs, except for Run 6 which had a feed rate of about 1.3 kg/hr (3 lb/hr). Two different feed rates were used when firing the coal-RDF powder mixtures in order to examine residence time effects.

The coal and RDF powder had been previously ground to minus 149 μ (-100 mesh). Each fuel was dried in a vacuum oven overnight to remove moisture before firing. The lower moisture content improved the feeding of the fuel. However, feeding problems were still encountered with the RDF powder. The lower density and heat content of the RDF powder required that the RDF powder be fed at a volumetric rate about 4 times that of the coal.

Although the feeder was modified to provide feed rates

⁺Illinois No. 6 Coal is a midwestern bituminous coal

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approaching 1.81 kg/hr (4 lb/hr), the pure RDF powder could only be fed at a maximum rate of about 0.68 kg/hr (1.5 lb/hr). The apparent reason for this was that the pure RDF powder tended to settle and pack more solidly in the feeder than did the other fuels and the particles could not be entrained rapidly and smoothly enough into the primary air stream to maintain combustion conditions comparable to those for coal. Consequently, the RDF powder was being burned at excess oxygen levels. It should be noted that none of these problems were encountered when the RDF powder was mixed with coal. In fact, the 50-50 RDF powder-coal mixture appeared to feed better than any of the other fuel combinations studied.

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TABLE 14. RESULTS OF THE COMBUSTOR EXPERIMENTS⁺

Run No.	Fuel Type	Feed Rate kg/hr (lb/hr)	Wall Temp (a) Average °C (°F)	Approximate Residence Time In Furnace Sec.	PPM			%		Wt % (in ash)	
					CO	SO ₂	NO	CO ₂	O ₂	C	H
1	Coal	0.54 (1.2)	946 (1735)	0.85	550	2800	550	13.0	6	13.2	0.2
2	RDF Powder	<0.9 (<2)	899 (1650)	3.71	100	60	150	14.4	9	8.1	0.3
2a	RDF (b) Powder	<0.9 (<2)	871 (1600)	~4	<300	--	--	--	10.5	1.2	--
3	75% Coal (c) 25% RDF Powder	0.54 (1)	963 (1765)	2.06	550	2200	--	15.8	6	24.1	0.5
4	75% Coal (c) 25% RDF Powder	0.9 (2)	899 (1650)	0.96	320	2000	--	16.0	6	11.9	0.2
5	50% Coal (c) 50% RDF Powder	0.9 (2)	960 (1760)	0.98	140	1500	--	16.4	5	4.0	0.2
6	50% Coal (c) 50% RDF Powder	1.36 (3)	935 (1715)	0.93	220	1500	--	14.4	3	9.6	0.2

(a) Thermocouple readings at 1.27 cm (0.5 in) from inside wall; inside wall temperature approximately 204°C (400°F) higher.

(b) Minus 74µ (-200 mesh) RDF powder; and all other fuels minus 149µ (-100 mesh).

(c) Weight percent basis

⁺Conducted at Battelle Columbus Laboratory

Wall temperatures in the combustor were measured with Pt-Pt 10% Rh thermocouples embedded in the ceramic layer to within 1.27 cm (0.5 in) of the interior reactor wall. Pyrometer readings indicated a temperature gradient of about 204°C (400°F) between the inside wall and the location of the thermocouples. Thus, the average temperature readings shown in Table 14 are about 204°C (400°F) below actual conditions.

In most of the runs, the furnace was initially heated with

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methane to above 1232°C (2250°F) (optical pyrometer) before switching to the solid fuel. In burning the solids, however, the temperature was found to generally drop to between 1182 and 1093°C (2160° to 2000°F) before stabilizing conditions were reached. The lower heat content of the solid fuels probably causes this temperature drop. Temperatures below 1232°C (2250°F) are desirable in these experiments because of the low fusion temperature of the ash from the RDF powder.

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Residence times ranged from 0.85 to 3.7 sec. The relatively high values for the pure RDF powder (Runs 2 and 2a) were due to the overall lower air flow rates that had to be used with this fuel.

Exhaust Gas Analysis

The gaseous species CO, CO₂, O₂ and SO₂ were continuously monitored during the duration of each run. The oxygen and CO levels were used to identify stable firing conditions. When the oxygen level appeared to level off at around 5 to 6 percent, the particulate samples were taken. The latter required about 10 to 15 min. The gas concentrations shown in Table 14 were recorded during stable firing conditions and are reported on a dry basis.

Several different analytical methods were used to measure the different gaseous species;

<u>Gas</u>	<u>Measurement Method</u>
CO	NDIR
CO ₂	NDIR
O ₂	Paramagnetic
SO ₂	Potentiometric
NO	NDIR

The results of the gaseous measurements taken during the combustion tests (CO, CO₂, O₂, SO₂ and in some instances NO) are presented in Table 14. The carbon and hydrogen content of the ash from each firing were determined and are also presented in Table 14.

It is apparent from the carbon content measured in the ashes that complete burnout was not achieved at the temperatures and residence times used. As mentioned earlier, temperatures below 1232°C (2250°F) were preferred due to the low fusion temperature of the RDF ash. In general, burnout was better for the RDF powder and the RDF powder-coal mixtures than with the raw coal, with the exception of Run 3. The reason for the high carbon content found in the ash from Run 3 is not known. The pure RDF powder

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and the 50-50 RDF-coal mixture of RDF and coal demonstrated the most effective combustion with only four percent carbon in the ash.

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The CO levels encountered in these test firings were somewhat high but not exceptional for the small combustor used. The CO values further demonstrate the more effective combustion performance of the RDF powder and RDF powder-coal mixtures compared to coal. The data further demonstrate the very low sulfur content of the RDF powder, which generated about 60 ppm SO₂ on combustion. The data also showed that the RDF powder produces less NO (150 ppm) than might be expected from the measured nitrogen content of the fuel (~0.7 percent). It is likely that nearly all of the NO produced during combustion is derived from fuel-nitrogen since the temperatures are too low for much thermal NO to be formed. It is evident that combustion of the RDF powder produces much less SO₂ and NO than the coal.

As seen in Table 14, the SO₂ emission levels drop significantly when the coal is co-fired with RDF powder. At first glance, the drop in SO₂ appears to be about that expected from adding a fuel with little or no sulfur content to the coal (within experimental error). However, taking into account the lower content of combustibles in the RDF powder, it would appear that the drop in SO₂ is more than would occur on a purely additive basis. Preliminary calculations indicate that the SO₂ emissions should be 20 to 35 percent higher than measured for the RDF/coal mix. It is postulated that the high alkaline content of the RDF powder is effective in capturing some of the SO₂ generated during combustion.

Because of the variation in combustion parameters, e.g., temperature, the lower oxygen level in Run 6 (compared to Run 5), and the uncertainty in some of the data from Run 3, the effects of residence time on the combustion of the RDF powder/coal mixtures could not be evaluated. However, it does appear that longer residence time and/or higher temperatures are needed for good burn-out of all the fuels evaluated (except possibly for Run 2a).

In summary, the RDF powder appears to burn more readily than coal, and the SO₂ and NO emission levels from RDF powder are lower than from the coal. The RDF powder/coal mixtures burn well, especially the 50-50 mixture.

POWDER/OIL SLURRY FIRING

A slurry of RDF powder and distillate oil was fired in the Battelle 37 kw (50 hp) research boiler facility shown in Figure 16. This slurry was prepared without the use of a dispersant agent. The slurry burned satisfactorily although fuel pumping problems were experienced when the powder settled out of the

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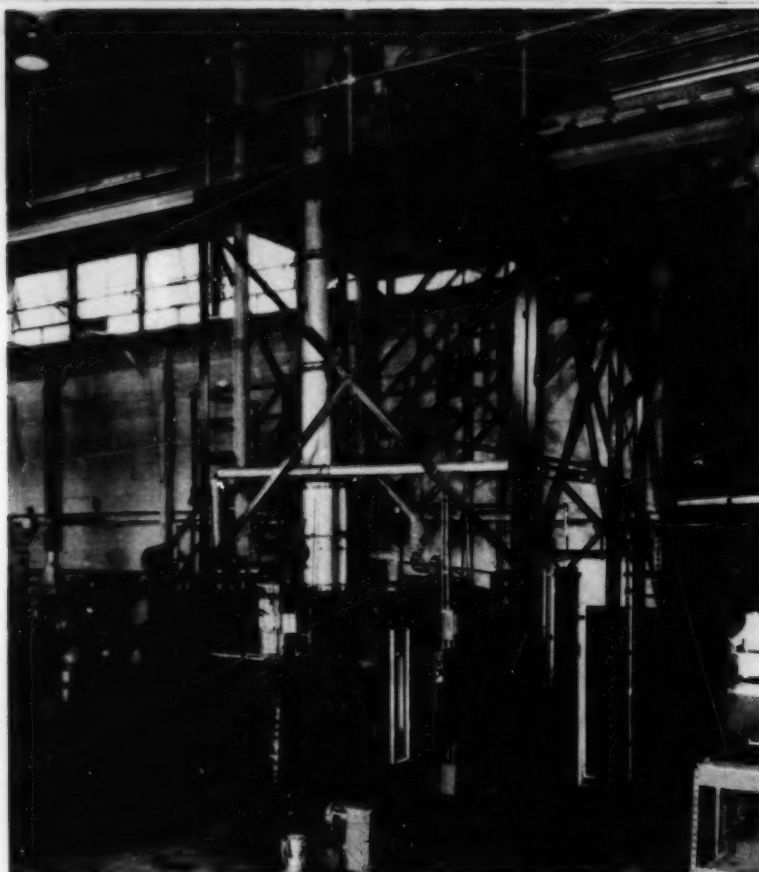


Figure 16. Battelle-Columbus Combustion Research Facility

distillate oil. The primary objective of these combustion tests was to demonstrate the feasibility of burning the RDF powder in an oil slurry.

Experimental Approach

In these experiments, RDF powder was co-fired with No. 2 fuel oil in a 37 kw (50 hp) fire-tube boiler with firing rates between 1.37 and 1.48×10^9 j/hr (1.3 and 1.4×10^6 BTU/hr). The slurry ignited easily and burned well. In order to feed the powder/oil mixture into the boiler without plugging the nozzle, a special, large bore oil nozzle was used in the boiler.⁺ The nozzle used is rated at approximately 136 kg/hr (300 lbs/hr). Four atomizing air jets [≈ 0.4 cm (0.0625 in) diameter] intersect the

⁺RIPCO, South Charleston, West Virginia

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The nozzle used required in excess of 27 kg/hr (60 lbs/hr) atomizing air in order to ensure adequate fuel vaporization. Low air flows through the air jets 27 kg/hr (60 lbs/hr) give rise to high CO levels (650 PPM) and high smoke numbers (10+) even though adequate primary air is available for complete combustion.

Pumping and feeding of the powder/oil mixture proved to be the most difficult phase of the combustion studies. Conventional gear pumps would be likely to jam so a screw pump was used to feed the fuel mixture. This pump did not experience any pumping problems at the 15 percent powder concentration, but it did plug at powder concentrations above 15 percent. At the higher concentrations, feed lines plugged and valves jammed. One valve jammed in such a manner that the fuel feed lines did not close when the flame went out. As a result several gallons of oil were injected unburned into the main combustion chamber.

Although there were no combustion problems experienced when firing the 30 percent powder/oil mixture, extended runs could not be sustained. The flame produced appeared to be very bright yellow and was quite stable. This experiment lasted only 30 minutes because the fuel feed lines plugged and the tests could not be continued.

RESULTS

Table 15 summarizes the results of the combustion tests for the 15 percent by weight powder/oil mixture. Visual examination of the flame indicated good combustion with the generation of only a few "sparklers". Smoke numbers could not be determined with any degree of accuracy because of the presence of a yellowish tint to the soot. Apparently the combustion of the RDF powder somewhat "colored" the soot particles. This same phenomenon has been observed when firing residual oils containing trace metals. At excess air levels above 6 percent, CO levels were reasonably low. SO₂ and NO levels are consistent with predictions based on fuel analyses.

A particulate loading of 800 mg/Nm³ was measured for the powder/oil mixture. This is relatively high compared to the levels normally recorded for residual oil (100 mg/Nm³ and distillate oil 20 mg/Nm³). Chemical analysis of the filter catch indicated that less than one percent of the particulate was unburned carbon. This result confirms the observation that the powder/oil slurry underwent complete combustion. These results also show that the high inorganic content of the RDF powder cause high particulate loading during combustion.

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As noted earlier, the slurry with 30 percent powder burned well; however, sustained boiler operation could not be achieved

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because of fuel line and pump plugging problems. Table 16 summarizes the data for the 30-minute run.

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Based on the limited tests conducted, it appears that the RDF powder can be fired in slurry form. However, the high inert content of the powder will cause significant particulate loading. In addition, a stabilizing agent is needed to maintain a homogeneous mixture of powder and oil to inhibit settling in the fuel handling system.

TABLE 15. SUMMARY OF 15% RDF POWDER IN DISTILLATE OIL COMBUSTION EXPERIMENTS. BOILER FEED RATE WAS 36 KG/HR (80 LB/HR)

O ₂ % (dry)	CO ₂ % (dry)	CO PPM	NO PPM	SO ₂ PPM	Particulate Loading Mg/Nm ³
8.4	9 1/2	20	125	55	--
6.0	10.4	55	120	60	--
5.3	10.7	211	125	65	--
6.5	10.2	25	112	60	800

TABLE 16. SUMMARY OF 30% RDF POWDER IN DISTILLATE OIL COMBUSTION EXPERIMENT

O ₂ % (dry)	CO ₂ % (dry)	CO PPM	NO PPM	SO ₂ PPM
6.8	10.0	25	140	70
5.8	11.0	235	140	75
6.2	10.5	85	140	65

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